A REVIEW OF EXPANSIVE PHENOMENA IN WAGENBURG NORTH TUNNEL

Por

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Abstract

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The paper deals on tunnelling and swelling in anhydritic-gypsiferous claystones. The geology of the *Gipskeuper* in Baden-Württemberg (Germany) and the phenomenology of expansions in Wagenburg North tunnel are described. Consistent swelling triggering events, mechanisms and exhaustion causes were identified using a thermo-hydro-chemo-mechanical theoretical analysis. It is suggested that long-term swelling in tunnels excavated through anhydritic-gypsiferous claystones is a result of solvent-way gypsum crystal growth due to ventilation induced groundwater evaporation and rock drying; an opposite concept to the usual consequences of drying in argillaceous materials, which causes shrinkage strains.

Key words: anhydrite, gypsum, clay, rock, tunnel, swelling, ventilation.

Resumen

El artículo trata sobre construcción de túneles y expansividad en arcillolitas anhidrítico-yesíferas. Se describe la geología del *Gipskeuper* en Baden-Württemberg (Alemania) y la fenomenología de las expansiones en el túnel Wagenburg Norte. La identificación de los eventos detonantes de las expansiones -así como de los mecanismos y causas de su decaimiento-, se fundamentó en un análisis teórico termo-hidro-químico-mecánico. Se sugiere que las expansiones a largo plazo en túneles excavados en arcillolitas anhidrítico-yesíferas es el resultado del crecimiento vía solvente de cristales de yeso por causa de la evaporación del agua del terreno y la desecación de las rocas, ambas inducidas por la ventilación; un concepto opuesto a las consecuencias usuales del secado de los materiales arcillosos, el cual causa deformaciones de contracción.

Palabras clave: anhidrita, yeso, arcilla, roca, túnel, expansividad, ventilación.

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Introduction

A large amount of tunnels in Baden-Württemberg (Southwestern Germany) are located in outcrops and buried formations from the Keuper (Triassic - Germanic Basin). Expansive phenomena have been observed in some of these tunnels, specifically in stretches excavated through anhydritic-gypsiferous claystones from the *Mittlerer Gipshorizont* (*Gipskeuper*, Middle Keuper); a situation that is clearly illustrated in table 1, which indicates the location of roadway and railway tunnels within the Keuper. The swelling behavior of the *Mittlerer Gipshorizont* has caused high heave in unreinforced tunnel floors and strong swelling pressure against inverts of tunnels with resisting supports. Recurrent damages and failures in both drainage systems and concrete flat-slabs and invert-arches have been it necessary continuous repair measures and reinforcements.

The swelling potential of the *Gipskeuper* in general -and the *Mittlerer Gipshorizont* in particular-, has been studied during decades in Germany since expansive phenomena were detected in Weinsberger tunnel, Kappelesberg tunnel and Schanz tunnel at the end of the 19th century. Swelling induced rock deformation patterns in these cases were described in detail by **Binder (1864)** and **Schachterle (1926, 1929)**. Later, precise information on swelling-time relationships came from long-term measurements of heaves and swelling pressures carried out in the Wagenburg Tunnel System during different periods since 1943 until 1992 (**Krause & Wurm, 1975**; **Krause, 1976**; **Wichter, 1985**; **Nagel, 1986**; **Paul & Wichter, 1996**; **Paul & Walter, 2004**), in the test gallery of Freudenstein tunnel between 1987 and 1998 (**Kirschke, 1987**; **Fecker, 1992**; **Wittke-Gattermann, 1998**; **Amstad & Kovári, 2001**), in the test zone of Heslach II tunnel between 1987 and 1988 (**Wittke, 2000**) and in their operative tube between 1991 and 2003 (**Wittke, 2006**). In all of these cases heaves and swelling pressures evolved at high rates and without signs of attenuation.

Since the comprehensive studies on swelling of sulphate-bearing rocks were published by **Sahores (1962)** it has been generally accepted that two uncoupled mechanisms occur when anhydritic-gypsiferous claystones are soaked: (i) a short term "physical swelling" –due to the expansion of clayey host matrix–, and (ii) a long term "chemical swelling" –due to the transformation of anhydrite into gypsum in an thermodynamically open system, with a volumetric increase of approximately 62%, as shown in figure 1. If the volumetric increase is partial or totally inhibited in either of these mechanisms, then a corresponding swelling pressure is generated. From that time this criterion -usually called "the anhydritic theory"-, is the key referent of

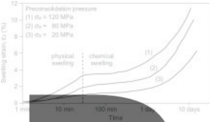

Figure 1. Classic interpretation of swelling mechanisms in anhydritic-gypsiferous claystones presented on an original figure by Smoltczyk (1992).

geological and geotechnical studies of the *Gipskeuper* developed in Germany.

The investigations by **Schlenker (1971)** and **Lippmann (1976)** focused on the quantitative mineralogical composition of the *Gipskeuper* host matrix revealed the occurrence high contents of interstratified expansive clayey minerals. On the other hand, the studies by **Rauh & Thuro (2006)** and **Rauh et. al. (2006)** showed the dependence of the anhydrite swelling potential on their textural form, emphasizing the importance of the surface available to interact with water on the swelling mechanisms of this type of rock. With regard to laboratory tests, long-term expansions without signs of attenuation can be observed in both free swelling tests and swelling pressure tests on undisturbed samples recovered from the *Gipskeuper* in Wagenburg tunnel (**Henke, 1976**) and in the test gallery of Freudenstein tunnel (**Kirschke, 1987**; **Kirschke et. al., 1991**), as shown in figure 2. Similar results are reported by **Pimentel (1996)**, who used a protocol of swelling under loading on undisturbed samples from the *Gipskeuper*.

Nowadays certainly there is an elevated knowledge on the mineralogical composition of the *Gipskeuper* and on the phenomenology of their swelling behavior. However, this situation is not in agreement with the understanding of the mechanisms behind the swelling. The "physical swelling" of anhydritic-gypsiferous claystones occurs even in the absence of active clay minerals and is characterized by asymptotic swelling-time relationships due to it is controlled by suction changes until saturation (**Alonso & Berdugo, 2005**). However, theoretical considerations and experimental evidences indicate that the transformation of anhydrite into gypsum is a highly time-consuming isovolumetric process in which anhydrite is dissolved as fast as secondary gypsum precipitates (e.g. **Holliday, 1970**;

Table 1. Tunnels in Baden-Württemberg excavated through rocks from the Keuper according to Krause (1976), Wittke (2000) and Amstad & Kovári (2001).

Stage	Upper Keuper						Middle Keuper						Lower Keuper		
								GIPSKEUPER							
TUNNEL	*Rätsandstein*	*Knollenmergel*	*Stubensandstein*	*Obere Bunte Mergel*	*Kieselsandstein*	*Untere Bunte Mergel*	*Schilfsandstein*	*Estherienschichten*	*Mittlerer Gipshorizont*	*Dunkelrote Mergel*	*Bochinger Horizont*	*Grundgipsschichten*	*Lettenkeuper*	Tunnel Type	Tunnel Length (km)
Achdorfer Weg														B	0.5
U-Bahn Bopser-Degerloch														B	1.3
S-Bahn Hasenberg														B	2.1
Bergau Vaihingen														B	0.2
Hasenberg														B	0.3
Herrenberg														A	0.6
Tübingen														B	0.3
Schnarrenberg														B	0.3
Schwab														A	0.1
Kriegsberg														B	0.6
Engelberg-Base									E					A	2.5
Freudenstein Test									E					C	-
Wagenburg North									E					C	-
Wagenburg South									E					C	0.8
Wagenburg Test Tunnels									E					C	-
Heslach II									E					A	0.8
Prag									E					B	0.7
Schanz									E					B	0.9
Kappelesberg									E					B	1.4
Weinsberger									E					B	0.9
Hölzern														A	0.5
Sulzfelder														B	0.3
Lerchenberg														B	0.4
U-Bahn Torstr.														B	0.1
Schwaikheim														B	0.3
Gölshauser														B	0.1
Hessentaler														B	0.1

A: roadway tunnel, B: railway tunnel, C: test tunnel, E: stretches affected by expansive phenomena.

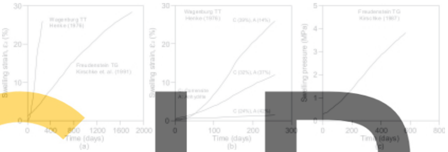

Figure 2. Swelling tests on undisturbed samples recovered from the *Gipskeuper* in Wagenburg tunnel and Freudenstein tunnel.

Ortí, 1977; **Pina et. al.**, 2000; **Pimentel**, **2003**; **Berdugo**, **2007**). The excess in hydrated calcium sulphate (62% in volume) could be either transported in aqueous solution or it could precipitate partially in the form of gypsum in open discontinuities of the host clayey rock. So, the classic criterion on long-term "chemical swelling" of anhydritic-gypsiferous claystones is difficult to accept and more realistic mechanisms must be considered.

This paper is a contribution to the study of mechanisms underlying long-term expansive phenomena affecting tunnels excavated through anhydritic-gypsiferous claystones, which uses a case from Baden-Wüttenberg as reference. Main compositional features of the *Gipskeuper* are summarized and the phenomenology of expansions in the tunnel is described. The swelling in the tunnel is analyzed as a thermo-hydro-chemo-mechanical (THCM) phenomenon using a theoretical framework founded on basic geochemical and thermodynamical principles, making it possible the formulation of consistent triggering swelling events as well as the identification of conditions conducing to either their evolution or exhaustion.

The *Gipskeuper*

Rocks in the Triassic Germanic Basin have been conventionally divided into three typical series: Bunter, Muschelkalk and Keuper; but only in the latest two of these series anhydritic-gypsiferous claystones occur systematically. A representative stratigraphic profile of the Keuper in Baden-Württemberg is presented in figure 3.

At the end of the Muschelkalk sedimentation within the Germanic Basin descended, so the Keuper sediments were deposited in wide flat areas. The basement received sediments from sea currents, rivers and deltas, wind, processes of evaporation and flash floods. At this time the climate was continental and arid, but changed to semi-humid conditions until the end of the Keuper (**Geyer & Gwinner**, **1991**). The *Gipskeuper* (Middle Keuper) is a sequence of clays and silty to dolomitic marls showing a wide range of colors. Red to violet sediments are indicatives of an oxidizing environment while gray to greenish sediments are the confirmation of a reducing environment. Evaporation of the saline sea water led to the formation of anhydrite, gypsum and halite crystals (**Aigner**, **1990**).

In general, the *Gipskeuper* consists in heterogeneous mixtures of anhydrite and gypsum in a hard clayey matrix, as shown in figure 4 and table 2. Expansive clays are partial components of host clayey matrix; for example, Corrensite has been found in Baden-Württemberg (**Schlenker**, **1971**; **Götz**, **1972**; **Henke**, **1976**; **Lippmann**, **1976**) -as illustrated figure 5-. Corrensite is a 1:1 regular interstratification of

Table 2. Mean composition and physical properties of the *Gipskeuper* (several sources).

Mineralogical composition (%)						Gs	w	ρt
Anh	Gyp	C	Carb	Qtz	Feld		(%)	(Mg/m³)
30-75	1-20	5-20	0-20	5-20	1-5	2.60-2.84	0.5-4.5	2.2-2.4

Anh: anhydrite, Gyp: gypsum, C: clay, Carb: carbonate, Qtz: quartz, Feld: feldspar.

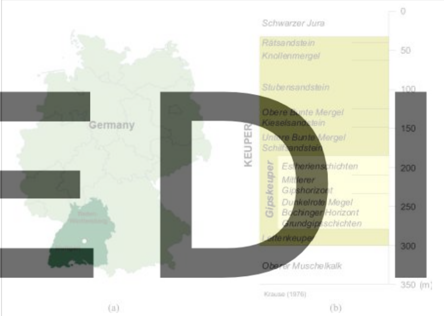

Figure 3. (a) location of the zone under study, (b) stratigraphic profile of the Keuper in Baden-Württemberg.

Figure 4. Undisturbed sample from the *Gipskeuper* (Amstad & Kovári, 2001).

trioctahedral chlorite and trioctahedral smectite, also called "swelling chlorite". However, Illite and Chlorite dominate the clay fraction in Triassic anhydritic-gypsiferous claystones and non-expansive clays have been detected as principal clay matrix components in many tunnels excavated through the the *Gipskeuper*; for example, Kappelesberg (**Krause**, **1976**; **Kurz & Spang**, **1984**) and Freudenstein (**Kirschke**, **1987**; **Kirschke et. al.**, **1991**).

In Baden-Württemberg the *Gipskeuper* shows a constant profile which can be divided, basically, as follows (see figure 5): the *Grundgipsschichten* (basal gypsum layers), *Bochinger Horizont* (Bochinger bed), *Dunkelrote Mergel* (dark red marls), *Mittlerer Gipshorizont* (middle gypsum bed) and *Estherienschichten* (Estheria beds). In Stuttgart a distinction must be made between two different layers associated with the *Mittlerer Gipshorizont*: (i) the leached gypsiferous level, and (ii) the unleached anhydritic

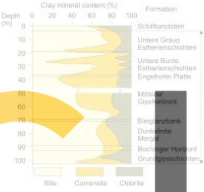

Figure 5. Lithology and composition of clayey matrix of the Gipskeuper in Baden-Württemberg (modified after Schlenker, 1971).

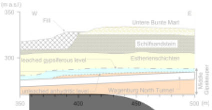

Figure 6. The leaching front (gypsiferous level) and the anhydritic level in Wagenburg North tunnel (Stuttgart, Baden-Württemberg). Original figure modified after Nagel (1986), Paul & Wichter (1996) and Amstad & Kovári (2001).

level. This distinction is illustrated in figure 6 using the case of Wagenburg North tunnel as reference. Above the anhydritic level anhydrite has been converted into gypsum in geological times; whereas above the gypsiferous level gypsum has been dissolved and transported away by the groundwater (**Wittke, 2000**).

Information regarding the chemical composition of groundwater in tunnels excavated in the the *Gipskeuper* in Baden-Württemberg is either incomplete or inconclusive. According to **Krause (1976)** for existing tunnels in the Keuper the total discharge varies between 0.5 and 2 litres per second and the sulphate content in groundwater near the leached gypsiferous level is above 1000 ppm. Data on groundwater sulphate content in tunnels have been reported by some authors, but only concerning the possibility of sulphate attack to concrete. The occurrence of macroconstituents as calcium, magnesium, sodium and potassium -which have an essential role in the interaction between sulphate-rich water and sulphate-bearing rocks-, is not reported in the German literature on the subject. Values of sulphate content reported by some authors are presented in table 3.

The Wagenburg North tunnel

The Wagenburg tunnel connects the centre with the eastern part of Stuttgart. Three independent structures must be distinguished in this case; each one characterized by particular cross sections, but affected by similar expansive phenomena (see figure 7): (i) the North tunnel, (ii) the South tunnel, and (iii) the Test tunnels. These structures are located mainly within the *Mittlerer Gipshorizont* and strong swelling is restricted to the innermost 250 m, just in the zone in which the tunnels cross the transition from the leached gypsiferous level to the unleached anhydritic level (see figure 8). Unfortunately, information on the hydrogeological regime in the rock massif is unknown.

The north tunnel was completed in 1942. It has a length of 800 m and a maximum overburden near 80. It has a horseshoe cross-section and a concrete lining that covers the roof and walls, but the floor was unlined and has remained in this state ever since construction (**Götz, 1972**). Expansive phenomena measured since 1943 until 1970 were

Table 3. Sulphate content in groundwater from some tunnels excavated in the *Gipskeuper*.

Tunnel	SO4 concentration (ppm)	Reference
Weinsberg tunnel	up to 1500	Gremminger & Spang (1978)
Kappelesberg tunnel	1957 - 2755	Krause & Wurm (1975)
Freudenstein tunnel	up to 5600	Berner (1991)
Engelberg Base tunnel	> 8600	Kuhnhenn et. al. (1979)

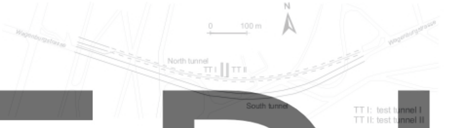

Figure 7. Localization of structures in Wagenburg tunnel system.

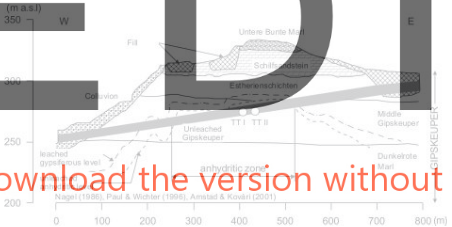

Figure 8. Geological longitudinal section of Wagenburg Tunnel System.

described in detail by several authors (e.g. **Götz, 1972**; **Krause, 1976** and **Nagel, 1986**). The evolution of floor heave in this tunnel was analyzed for this paper using original data by **Krause (1976)** and **Nagel (1986)**, and is presented in figure 9. After twenty seven years of monitoring since 1943 a maximum floor heave of 1029 mm was measured in the axis of the section and, in general, no asymptotic trends were observed in any of the control stations (see figure 9c).

Weathering and gypsum growth induced swelling certainly affected the foundation material in Wagenburg north tunnel, as illustrated in figure 10. **Krause (1976)** reported that *".....inspections of foundation materials in Wagenburg during the early 70's -and also in Kappelesberg tunnel-, have shown that the original anhydrite was converted almost completely to gypsum in the heaving floors without showing any visible increase in volume. Except for strongly leached sections, the sulphate rocks have remained essentially compact".*

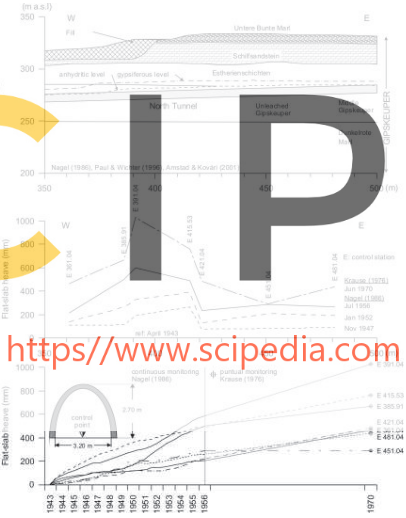

Figure 9. Geology and total floor heave in Wagenburg north tunnel after 27 years of monitoring (modified after Krause, 1976 and Nagel, 1986).

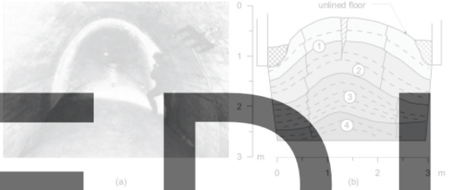

Figure 10. (a) Wagenburg north tunnel in 1970 in an image by Spaun (1974). (b) Distribution of gypsum crystals along the weathered subsoil profile according to Krause (1977) & Nagel (1986): (1) segregate-impure gypsum crystals and macrocrystals, (2) segregate-pure gypsum crystals in fine sheets, (3) gypsum macrocrystals and fibrous gypsum, (4) transition between (1) and (2).

Analysis of swelling mechanisms

Background

Observations by **Krause (1976)** in Wagenburg North tunnel reveal that transformation of anhydrite into gypsum is not a reasonable explanation for long-term expansive phenomena that affected the foundation material. In fact, these observations are unequivocal evidences of the epitaxial growth of gypsum on anhydrite; a process that generates a gypsum film protecting the anhydrite from the water action (**Ortí, 1977; Pina et. al, 2000; Berdugo, 2007**).

In opinion of **Wittke & Rißler (1976)** and **Wittke & Pierau (1979)** the water supplied by the natural ventilation was the triggering event for expansive phenomena that affected Wagenburg North tunnel. These authors indicate that during the warm period and just after construction the air flowing into the tunnel -with a water vapour concentration between 8 and 15 g/m^3-, provided to the unlined floor approximately 6 to 10 m^3 of water daily and caused both the weathering and the swelling of the rock (see figure 11). Therefore, a mechanism of "physical swelling" of the clayey matrix is defined as triggering event for expansions.

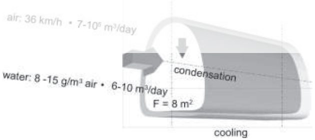

Figure 11. Possible quantity of condensation water as a consequence of natural ventilation in Wagenburg North Tunnel (modified after Wittke & Pierau, 1979).

The hypothesis of Wittke and co-workers was discussed by **Pimentel (2003)** as follows: *«In the past is was incorrectly assumed by Wittke & Rissler (1976), that during the driving of a tunnel and before lining, the swelling process will be activated on the surfaces exposed to air circulation with high but not saturated relative humidity. This concept does not consider unloading and gravitation. On the other hand, exposed clayey rock will in contact with circulating wet air, although it's hygroscopic property, dry out and shrink but not swell. The circulating air will evaporate the free water and some molecules in the diffuse layer of the exposed surfaces. Due to this evaporation, the salinity in the diffuse layer will increase and the thickness of the diffuse layer will shrink losing water molecules to the free water, which will be also evaporated. Additionally, it must be considered that due to unloading, shrinkage of the diffuse layer and due to the surface tension of water, negative pore pressure will be generated, producing water meniscus and tensile stresses. This tensile stresses can open some latent cracks. In summary, the exposition of rock surfaces with wet air with relative humidity less than 90% will contribute to a weathering process but not activate a swelling process».*

The criteria by Wittke and Pimentel are correct, but only partially. As shows figure 10b weathering and swelling certainly affected the foundation material of Wagenburg North tunnel, but in a more complex form than only due to condensation or evaporation of pure water. The growth of gypsum crystals in discontinuities and fissures of the expanded rock is an unequivocal indicator of rock weathering and swelling in the presence of calcium sulphate-rich water. Then, it is reasonable to assume that the swelling that affected the rock was related, almost partially, with gypsum crystal growth; but as a consequence of other mechanisms than just the anhydrite gypsification suggested by the "anhydritic theory".

Theoretical THCM analysis

Realistic mechanisms associated with the expansive phenomena observed in Wagenburg North tunnel can be formulated if the tunneling induced rock damage, drainage and ventilation are properly taking into account.

It is suggested that the tunnel excavation caused a damaged zone below the unsealed floor consisting in discontinuities along sedimentation planes and fissures -which is a typical effect of stress relief in underground excavations-. Below the damaged zone the rock can be considered nearly waterproof. In addition, tunnelling generated seepage of groundwater from the leached gypsiferous level located in the overburden, which drained naturally and was concentrated due to gravity in damaged zone. The leached gypsiferous level is a weathered material formed by anhydrite dissolution; therefore, it is reasonable to assume that high contents of calcium (Ca^{2+}) and sulphate ($SO4^{2-}$) are dissolved in the groundwater. Finally, tunnelling make it possible the interaction of the environment imposed by the natural ventilation -namely, relative humidity, temperature and wind velocity-, with the damaged rock causing either wetting or drying due to vapour transfer.

Vapour transfer from the groundwater to the tunnel, or vice versa, depends on the difference between the relative humidities imposed by the ventilation and the aqueous system. In this sense, the transfer occurs in the direction of the media with the lower relative humidity at rates regulated by the temperature and the wind velocity.

Vapour transfer in Wagenburg North tunnel was evaluated for this paper using data on extreme values for the vapour density suggested by **Wittke & Pierau (1979)**. The partial pressure of vapour (u_v) was calculated using the law of ideal gases (Eq. 1), assuming constant vapour densities of 0.008 and 0.015 kg/m^3 in the temperature range between 20 and 40ºC (see figure 11). On the other hand, the vapour pressure imposed by pure water at atmospheric pressure was calculated using (Eq. 2). In these conditions a theoretical dependence of the relative humidity (u_v/u_{vo}) on the temperature in the tunnel was obtained. So, the tunnel was assumed to be an ideal thermodynamically closed system. Due to the chemical composition of groundwater in the tunnel is unknown, characteristic values of relative humidity imposed by saturated sulphate solutions have been used as representative of the in situ conditions (see figure 12a).

$$u_v = \frac{\rho_v \, RT\,(T+273.15)}{M_w} \; [Pa] \qquad \text{(Eq. 1)}$$

u_v : partial pressure of vapour

ρ_v : vapour density $\left[\frac{kg}{m^3}\right]$

R : universal gas constant (8.314 $J\ mol^{-1}\ T^{-1}$)

T : (º)C

M_w : molecular mass of water (0.018 $kg\ mol^{-1}$)

$$u_{vo} = 136075\times10^{6}\; e^{\left(\frac{-5238.7}{T+273.15}\right)} \; [Pa] \qquad \text{(Eq. 2)}$$

T: (º)C

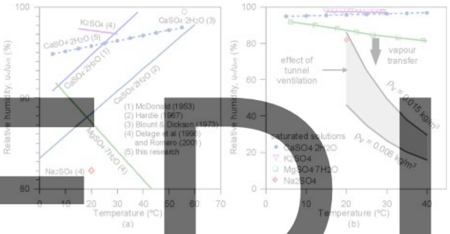

Figure 12. Analysis of vapour transfer for Wagenburg north tunnel based on relative humidities imposed by saturated sulphate solutions and values of vapour density suggested by Wittke & Pierau (1979).

The results of this analysis are presented in figure 12b. It is clear that if an ideal thermodynamically closed system holds for Wagenburg North tunnel, the relative humidity of the incoming flow of wet air is lower than the relative humidity in equilibrium with ideal saturated-sulphate solutions within a wide temperature range representative of the tunnel operation. Therefore, theoretically the vapour transfer could be only possible from the sulphate-rich groundwater accumulated in the damaged zone towards the tunnel through the unsealed floor, causing groundwater evaporation and rock drying, just in opposition to the hypothesis by Wittke and co-workers.

Evaporation is a two-step process that consists in a first step involving the transition from liquid to vapour phase at the liquid-vapor interface (vaporization); followed by a second step of vapour transport from the high concentration area at the evaporating surface to the low concentration area of the ambient air.

The evaporation of calcium sulphate-rich water unconditionally leads to high concentrations of dissolved calcium (Ca^{2+}) and sulphate ($SO4^{2-}$). This could be the triggering event of both the supersaturation in these species of the groundwater and the precipitation of gypsum crystals in open discontinuities and fissures of the damaged zone. Therefore, the long-term swelling of the foundation material in Wagenburg North tunnel could be related with a mechanism of solvent-way gypsum crystal growth, which evolved systematically due to an effective vapour transfer from the groundwater to the tunnel atmosphere in a weathered or damaged rock affected by the excavation works. At first, this interpretation is in agreement with the occurrence of gypsum crystals on the unleached anhydrite of the foundation material of the tunnel.

Discussion

In reality, ideal thermodynamical closed conditions do not occur in tunnels, as it was assumed in the analysis presented here. Erratic variations of the environmental relative humidity imposed by ventilation -without a clear dependence on temperature, even during the same season-, have been observed in several tunnels from different climatic zones. For example: Orange-Fish tunnel in South Africa, excavated through carboniferous expansive mudrocks from the Permian Beaufort formation (**Olivier, 1987**); Tournemire tunnel in France, excavated through Jurassic claystones and marls (**Rejeb & Cabrera, 2006**); ECRB cross drift of Yucca Mountain in USA, excavated through Tertiary ignimbrites (**Ghezzehei et. al., 2004**); and

Lilla tunnel in Spain, excavated through Triassic anhydritic-gypsiferous claystones from the Lower Ebro Basin (**Berdugo, 2007**). Nevertheless, measurements in these tunnels indicate that relative humidity due to ventilation is usually below 70%, with seasonal variations that also affect the temperature and both the wind velocity and the wind direction. These values are sufficient to cause the evaporation of groundwater.

When drying in the presence of poorly mineralized groundwater shrinkage of clayey rocks occur due to a loss of water mass without an effective transfer of solute mass. On the contrary, in the presence of highly mineralized groundwater an important precipitation of salts is possible and swelling due to crystal growth takes place.

The systematic solvent-way gypsum crystal growth explains the evolution of long-term swelling of anhydritic-gypsiferous claystones without a clear limit. On the other hand, the eventual exhaustion of this swelling mechanism would be related with exhaustion of the water supply from the tunnel overburden, changes in the chemical composition of groundwater, seasonal changes in tunnel ventilation –including variations in the wind velocity-, self sealing of fissures, and local instabilities within the damaged zone as a result of rock degradation by wet vapour flow.

Conclusive remarks

Lessons learned from Wagenburg North tunnel indicate that the presence of anhydrite does not unconditionally leads to the development of expansive phenomena in tunnels, showing the shortcomings of the classic "anhydritic theory" on swelling of anhydritic-gypsiferous claystones. Mechanical and hydraulic boundary conditions are important to interpret the phenomenology of long-term swelling in tunnels excavated through these materials; nevertheless, the role played by ventilation in the presence of highly sulphate groundwater should be properly considered in the study of triggering and exhausting events.

A thermo-hydro-chemo-mechanical (THCM) criterion for the interpretation of tunnelling induced swelling in anhydritic-gypsiferous claystones was presented. It is suggested that the occurrence of relict or induced discontinuities in the rock massif, a highly sulphated groundwater and the tunnel ventilation are indispensable requirements for generation of strong long-term swelling.

Experience indicates that tunnelling causes rock damage due to unloading, as well as wetting/drying cycles due to groundwater flow and ventilation. So, tunnels play the double role of permanent source-sink for liquid and gaseous phases.

Ventilation imposing relative humidities below the characteristics values for calcium sulphate-rich water causes a series of processes: (i) vapour transfer from the groundwater accumulated in the damaged zone towards the tunnel environment, (ii) rock drying, (iii) supersaturation in gypsum of the aqueous system, and (iv) precipitation/crystallization of gypsum in discontinuities and fissures of the damaged zone. As a result of gypsum crystal growth rock swelling occur, evolving at high rates if an effective vapour transfer from the groundwater to the tunnel atmosphere is permitted and rock discontinuities remain open.

Following the considerations presented above, it is suggested that swelling induced by gypsum growth in tunnels excavated through anhydritic-gypsiferous claystones is mainly a consequence of drying; an opposite concept to the usual consequences of drying in argillaceous materials, which result in the development of shrinkage strains. This understanding seems to be consistent with observations in Wagenburg North tunnel.

Finally, it should be added that mechanisms behind expansive phenomena in anhydritic-gypsiferous claystones cannot be fully identified at the scale of laboratory experiments. The field scale is unconditionally needed to understand the relevant processes.

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